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AEROFLEX smart power dolly: Towards efficient and mission-oriented long-haul vehicles

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Abstract

This paper is part of the AEROFLEX – AEROdynamic and FLEXible Trucks for Next Generation of Long Distance Road Transport – project. This project develops and demonstrates new technologies, concepts and architectures for complete vehicles that are energy efficient, safe, comfortable, configurable and cost-effective, while ensuring that the varying needs of customers are satisfied by being flexible and adaptable with respect to the continuously changing operational conditions. The paper concentrates on the concept and development of the distributed hybrid powertrain and the sophisticated energy and torque management system. In long-haul vehicles a distributed powertrain can be realized by installing additional power units in the towed vehicles like dollies and/or trailers. This pursues two main objectives: 1. reducing fuel consumption by the usage of electric powertrains and thus hybridizing the whole vehicle combination and 2. improving the driveability of longer and heavier long-haul vehicles by adding additional drive axles, which e.g. improve gradeability.

Keywords: efficient road transport, long-haul vehicle, hybrid powertrain, energy management system.

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Abbreviations

AEMPT	Advanced Energy Management Powertrain
AE-RR	Automotive Ethernet Router Repeater
CAN	Control Area Network
CEDR	Conference of European Directors of Roads
EBS	electronic brake system
EMS	European Modular System
GCW	Gross Combination Weight
GETMS	Global Energy and Torque Management System
HoD	Hybrid on Demand
HV	high voltage
ICE	Internal Combustion Engine
IEEE	Institute of Electrical and Electronic Engineers
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LHV	Long and Heavy Vehicle
LSM	Local System Management
MEO	Multi-level Energy Optimization
SAE	Society of Automotive Engineers
SPD	Smart Power Dolly
SOE	State Of Energy
TT	Tractor - Semitrailer

1. Introduction

The AEROFLEX – AEROdynamic and FLEXible Trucks for Next Generation of Long Distance Road Transport – project receives funding form the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 769658. It develops and demonstrates new technologies, concepts and architectures for long-range freight vehicles with optimized aerodynamics, powertrains and safety systems as well as flexible and adaptable loading units. The developments in combination target to improve transport efficiency by 18-33% while drawing up recommendations for implementing the results within European regulations and in the transport and logistics industry.

The key idea of introducing hybrid powertrain technology in the sector of long distance road transport is to combine the combustion engine of the pulling vehicle with electric drives in different towed vehicle units, thereby creating a distributed hybrid drive. This concept might allow installing a downsized combustion engine, which is supported by electric drives in the trailer units, if coupled to the truck. Consequently, such AEROFLEX vehicles (Fig. 1) would allow a flexible combination of intrinsically efficient vehicle units, which bring their own driveline into the combination when required.

Fig. 1: Flexible combination of driven vehicle units according to the AEROFLEX Grant Agreement (2017)

In the EU's funded project TRANSFORMERS (Grant Agreement No. 605170) an electrified semitrailer was combined with a conventional truck to create a hybridized vehicle combination, which reduces the fuel consumption even with a simple energy management strategy (Nitzsche et al. (2018)). Such a concept is referred to as Hybrid on Demand (HoD), as the hybrid powertrain is only formed when coupling tractor and semitrailer. In the TRANSFORMERS project, communication between the vehicle units was reduced to a minimum in order to make the system retro-fit capable. This approach is advantageous in terms of simple integration. However, it comes to limits if the electric power is raised to a level that substantially effects the overall vehicle behavior.
AEROFLEX aims to reduce fuel consumption up to 12% for European Modular System (EMS) vehicles by hybrid powertrain technology. Thus, to create an efficient system, all available powertrains – especially electric ones – must be integrated in an advanced energy and torque management. In the following, this system is referred to as Advanced Energy Management Powertrain (AEMPT).
For the assessment of fuel-saving potential and vehicle dynamics, a small number of suitable vehicle combinations had to be chosen, which are most likely to play a major role in the future European transport market. These investigations were based on the representative fleet for future EMS vehicles recommended by the FALCON Project, acronym for Freight And Logistics in a Multimodal Context (De Saxe et al. (2018)), funded by the CEDR. The fleet includes vehicles, which are already allowed in some member states of the EU and vehicles, which are tested in pilot programs. Unfortunately, expert interviews with representatives of the logistics marked did not result in a clear picture which vehicle combinations are the most favorable (Pöllath et al. (2018)). Thus, one common example out of the categories EMS 1 (up to 25.25 m length) and EMS 2 (more than 25.25 m length) was chosen. Wherever an assessment of specific configuration becomes necessary, the focus will be on the following vehicles:

- 4x2 Tractor – Semitrailer (TT): This is the most common configuration for long haul transport in Europe and therefore the base line for all assessment. The TRANSFORMERS project already showed the potential of such a configuration including an e-Trailer (Nitzsche et al., 2018).
- 6x2 Truck –Dolly – Semitrailer (EMS 1): This vehicle complies with the 25.25m length restriction for Long and Heavy Vehicles currently valid for Sweden, The Netherlands, Belgium, Denmark and Germany.
- 4x2 Tractor- Semitrailer-Dolly-Semitrailer (EMS 2): This configuration, also known as A-double is already in operation in Finland and Spain.

The EMS 1 combination is the major development focus of the AEMPT in AEROFLEX. In the most advanced configuration it consists of a 6x2 rigid truck with the Global Energy and Torque Management System (GETMS), the Smart Power Dolly (SPD), which has a steerable front axle and an electrically driven rear axle, and the TRANSFORMERS HoD semitrailer.

The benefit of the integrated powertrain technologies will be assessed in terms of two Key Performance Indicators (KPIs). KPI 1 is the fuel efficiency in [litre/(tonne-km)] and its corresponding percentage fuel consumption reduction compared to the reference vehicle (4x2 Tractor – Semitrailer). Thereby, the impact on fuel consumption is equivalent to the impact on the emissions of gram CO_2 per tonne cargo per kilometer. KPI 2 is the fuel consumption in [litre/km] and its corresponding percentage fuel consumption reduction compared to the reference vehicle. Additionally, the average speed has to be considered in the assessment, because a direct comparison of fuel consumption is only valid for similar average speeds in a specific cycle.

The section below gives insight into simulation results for the fuel consumption to underline the potential of the presented approach. The paper then focuses on the physical architecture of the distributed powertrain and gives a detailed description of the capabilities and features as well as the functional requirements of the newly developed system components. Several subsections deal with the basic requirements for the energy and torque management system, the local system management of the dolly and the vehicle-to-vehicle communication based on the Automotive Ethernet standard. Finally, the SPD as one of the central technology demonstrators is presented.

2. Analysis of distributed powertrains

This section presents the initial simulations to estimate the fuel saving potential for various vehicle configurations, electric power densities, payloads and mission profiles. The simulation results were assessed in terms of two main objectives. First, the findings can support the dimensioning of the electric powertrain components (battery and electric motor) of the SPD developed within the project. Second, they provide an overview of the overall potential of distributed powertrains for certain vehicle types in different applications independent of the AEMPT demonstrator vehicle. A detailed explanation of the simulations and results can be found in the public deliverable of Engasser et al. (2019).

The simulations have been conducted with TNOs in-house developed simulation model called Multi-level Energy Optimization (MEO). Fig. 2 shows the main structure of the model. The MEO modelling approach is based on a backwards vehicle model to derive the road load power from a drive cycle and vehicle specification. This road load power is the input to a Willans-line based powertrain model, to obtain a fuel consumption result. The effect of the hybrid system, consisting of the electric drive units in the HoD semitrailer and the SPD, is accounted for through a model extension. Thus, the current capabilities of the electric powertrain directly affect the power that is demanded from the internal combustion engine. Furthermore, a simple battery model is added to secure that the energy storage limitation meets realistic constraints. A scalable power split controller, that follows the approach proposed by Pham (2015), enables five different hybrid modes (Fig. 3): Charging while driving (C), Internal combustion engine only (ICE only), Motor assist (MA), Motor only with ICE idling (MO*) and Regeneration (R). Since the application considered is not a plug in hybrid vehicle, allowing for charging via the grid, the power split controller is designed to perform charge sustaining. Consequently, it aims to keep the State Of Energy (SOE) given by the battery model around 50%.

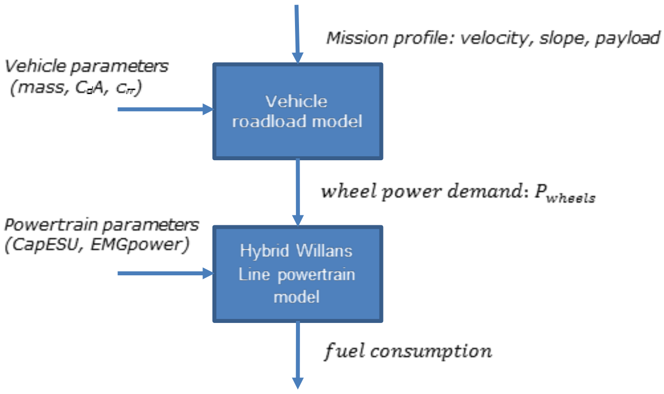

Fig. 2: Structure of the MEO modelling approach for conventional power vehicle

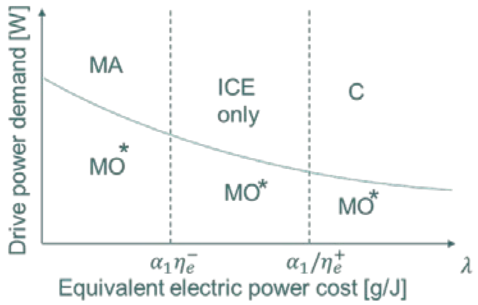

Fig. 3: Hybrid modes allowed by the power split controller

For the simulations three mission profiles from the EU Transformers project were considered relevant for long-heavy vehicles (see van Zyl et al. (2017)): flat highway (S1), frequent elevation changes (S3) and mountain pass (S4). The vehicle combinations TT, EMS 1 and EMS 2 were simulated with payloads ranging from zero to the maximum allowable payload of 40, 60 and 74 tons respectively, as well as intermediate steps of 10 tons. Different values of EMG power ranges from 80 – 720 kW and battery capacities from 1 – 60 kWh were used.

The limitation of the current model approach is the assumption, that the mission profile is achieved with respect to speed and torque. Given the fact that the mission profiles, which are based on a 40 ton tractor semitrailer, have been used for all simulations, the absolute fuel consumption figures for the heavier EMS 1 and EMS 2 combinations might be overestimated. Nonetheless, the results are regarded as sufficiently accurate for the purpose of the study.

Table 1 shows the main findings of the simulation study. The savings of fuel consumption in terms of litre per kilometre [l/km] are normalized against the conventional vehicle with an ICE and without hybridization for the same vehicle type, payload and mission profile as the corresponding figure. Thus, the relative values based on [l/km] or [l/tonne-km] become equal. The highest potential of hybridization can be seen in mountainous conditions, where the optimal hybrid configuration for each vehicle type and payload results in 13-17% reduction of fuel consumption. On ordinary (flat or with frequent elevation changes) motorways the maximum fuel reduction is reduced to 5-9% depending on the vehicle type and payload.

Table 1: Results of the simulations, optimal hybrid configuration and resulting increase in fuel efficiency in [l/km] normalized against the conventional vehicle with an ICE and without hybridization for the same vehicle type, payload and mission profile

		Flat highway (S1)		Frequent elevation changes (S3)		Mountain pass (S4)	
		20 [t]	full	20 [t]	full	20 [t]	full
TT	Battery [kWh]	20	60	20	60	20	60
	EMG [kW]	480	720	400	560	400	480
	Fuel efficiency [%]	6%	7%	5%	7%	15%	17%
EMS1	Battery [kWh]	20	60	20	60	20	60
	EMG [kW]	480	720	400	720	320	720
	Fuel efficiency [%]	6%	8%	5%	8%	13%	17%
EMS2	Battery [kWh]	30	60	20	60	30	60
	EMG [kW]	560	720	480	720	480	720
	Fuel efficiency [%]	6%	8%	5%	9%	15%	16%

Detailed simulation results of the EMS 1 vehicle at full load condition (GCW 60 ton) for different mission profiles are shown in Fig. 4. Based on the gradient of fuel saving in EMG and battery size direction an engineering-based selection can be made. Especially where the gradient is flat a smaller EMG or battery can be selected without significantly penalizing fuel savings.

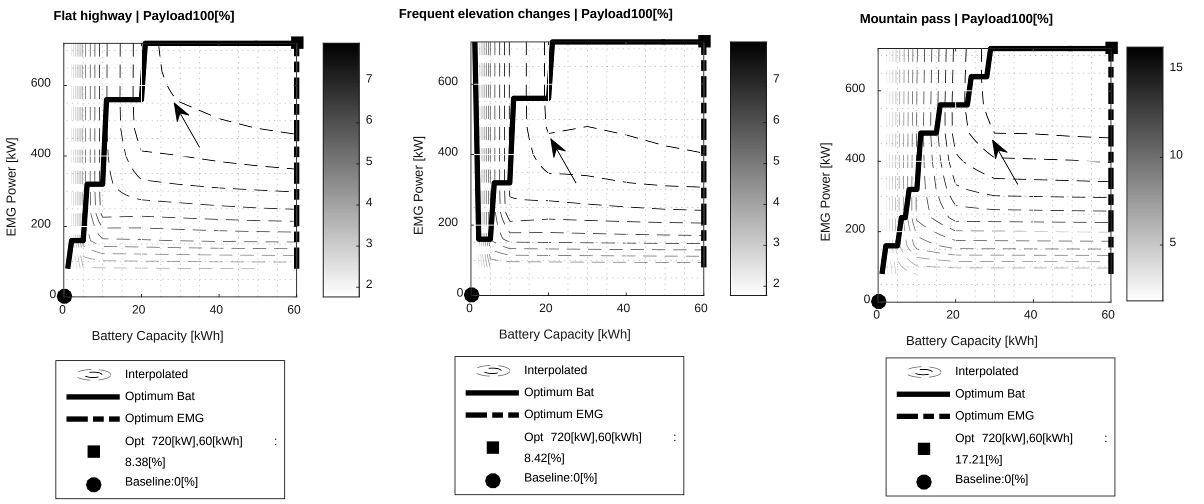

Fig. 4: Simulation results of EMS1 at full load (GCW 60t) for different routes with different combinations of EMG and battery size. The black arrows show engineering-based selected EMG and battery sizing based on the flat fuel savings gradient.

Calculation of the optimal EMG and battery size per ton Gross Combination Weight (GCW) resulted in 4 kW/ton and 0.35 kWh/ton, respectively. The simulations show different optimum in EMG and battery sizing for each vehicle configuration, depending on payload and mission profile. However, an optimal, vehicle specific hybrid component size points towards the following values:

- TT: 10-20 kWh battery capacity, 180-300 kW EMG power, providing a fuel saving of 5-15 % in l/km
- EMS 1: ~20 kWh battery capacity, 240-400 kW EMG power, providing a fuel saving of 5-15 % in l/km
- EMS 2: 20-40 kWh battery capacity, 240-480 kW EMG power, providing a fuel saving of 5-15 % in l/km

3. System design

A first simple version of a distributed powertrain was developed in the TRANSFORMERS project. Some details about the concept can be found in Nitzsche (2017) und Wagner (2017). In contrast to the TRANSFORMERS scenario, where the semitrailer is fitted with an electric powertrain and an internal energy management system, the AEROFLEX scenario allows for more sophisticated energy management strategies, because the usage of the

conventional engine and the electric engines can be better coordinated. The developed system architecture including the GETMS as a central system management in the tractor unit supports up to five trailer units which are equipped with a Local System Management (LSM). Fig. 3 gives an overview of the AEMPT structure.
The backbone of this distributed architecture is the Automotive Ethernet network, which connects the individual vehicle units. This technology has a substantially higher bandwith than a CAN based network and allows therefore to transmit more information.

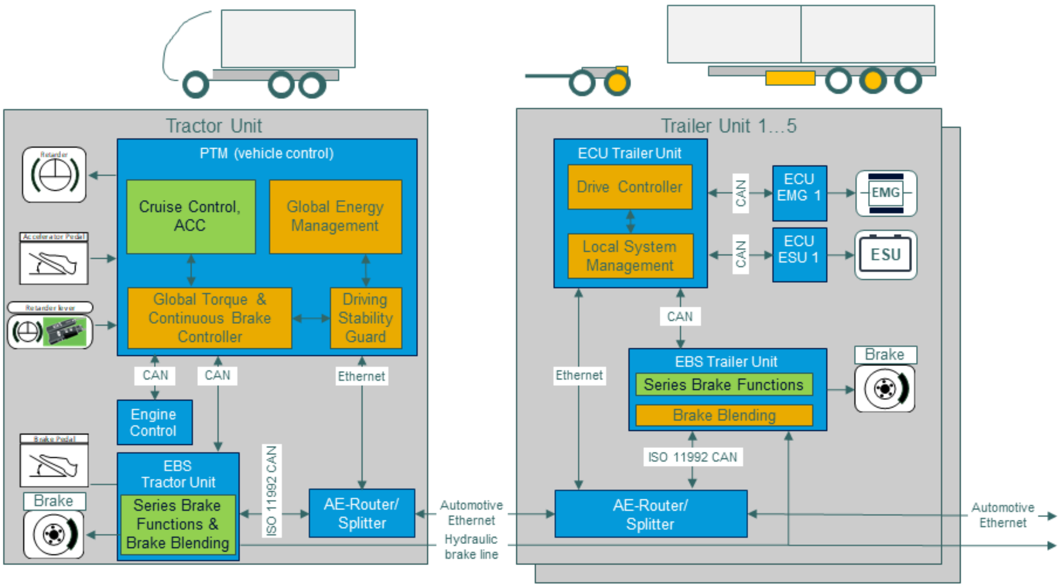

Fig. 5: Structure of the Advanced Energy Management Powertrain (AEMPT)

3.1. Global Energy and Torque Management System

The Global Energy and Torque Management System (GETMS) shall ensure that the combustion engine and electric drives act together as efficient as possible. In principle, the system has a parallel hybrid drive having distributed drive units. However there are some crucial differences to a non-distributed hybrid drive. Firstly there are multiple batteries. Accordingly, the energy management has to distribute power requests in a way to operate each battery at the desired SOC level. Secondly, as there is no HV-connection between the vehicle units, energy cannot be transferred directly between the vehicle units. The option to transfer energy “via the road” is not efficient. As a third and most demanding difference to a single unit hybrid drive, changing of trailer units may change the driveline configuration, as the trailer units can have different electric drives. In line with the basic ideas of AEROFLEX, the energy management shall allow to flexibly combine vehicle units. This means that the energy management has to adapt to a new vehicle configuration if vehicle units are coupled or uncoupled. As an example, the energy management system has on one hand to efficiently operate a tractor-e-semitrailer configuration including an electric drive in the trailer. On the other hand, if an electrically driven dolly and a conventional semitrailer is coupled to the vehicle, extending it to an EMS2 configuration, the energy management also has to efficiently operate that combination. To cope with such a drive system, the energy management receives information about the current state of charge, and currently available positive and negative power from each trailer unit. If there is sufficient energy available, the combustion engine is set into an efficient operating point and is supported by the electric trailer drives. Of course, additional electric power may be used to achieve a higher speed on high power driving situations like upward slopes. However, as improving energy efficiency is the major goal of AEROFLEX, the energy management shall not operate the drive units in a way which increases average speed on relevant cycles. When the endurance brakes are requested, brake power is shifted to the trailer drives to recuperate as much energy as possible.
Another task performed by the GETMS is the distribution of torques in a safe manner. Applying too much positive torque in the trailers in a cornering situation can negatively influence vehicle dynamics. For this reason, the GETMS includes a safety guard function to set limits to the energy managements torque requests. These limits are defined depending on the driving situation. When cornering, the limits are set tighter than when driving on a straight. The safety guard function has already been virtually tested by connecting it to a multibody vehicle dynamics model. Proving ground tests will follow with the vehicle combinations presented in chapter 3 in the next phase of the project.

3.2. Local System Management

The towed vehicles, e.g. Smart Power Dolly (SPD) or HoD-Trailer, are equipped with an Electric Motor/Generator (EMG), an Energy Storage Unit (ESU) and an ECU with a Local System Management (LSM). The LSM operates as a control system for the electric powertrain and its components. This includes initialization and shutdown routines, monitoring of the system states, error handling and the management of acceleration and brake requests. Brake requests can be generated by the GETMS and the trailer EBS. The GETMS distributes the endurance brake request from the EBS of the tractor unit among the available endurance brakes, e.g. the retarder brake of the truck or the EMGs of the towed vehicles. In contrast, the EBS of each trailer unit includes a so called brake blending function, which distributes the service brake request between the friction brakes and the respective EMG in order to recuperate as much energy as possible. Thus, the LSM constantly reports the brake related performance/capability parameters to the GETMS and the EBS of the trailer unit.
Furthermore, the LSM realizes an autonomous operation of the SPD independently from the tractor unit. For demonstration purposes the SPD is equipped with an industrial remote control, which enables maneuvering the vehicle by usage of the EMG, the friction brakes and the steered front axle. To ensure a safe operation without any interference between the operational modes an operator or driver can choose between common operation of the whole vehicle combination and autonomous operation by a switch at the SPD. Thus, the receiver of the remote control is only powered during autonomous operation. Additionally, the LSM can only send a brake request to the EBS of the SPD via the communication path that is usually used by the tractor unit. This communication path must be established by the operator or driver when changing the operational mode (see Fig. 6).

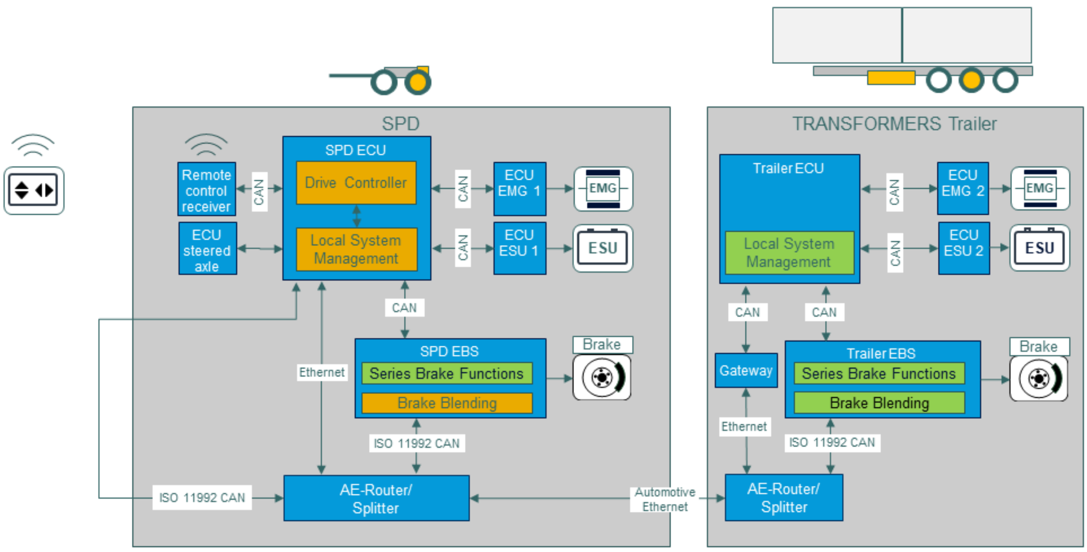

Fig. 6: Realization of the Advanced Energy Management Power Train during autonomous operation in the demonstrator vehicle

3.3. Vehicle-to-vehicle communication

For more than 20 years truck trailer communication in Europe is performed based on the ISO 11992 standard using CAN on copper cables as physical medium. Its protocol structure is similar to SAE J1939, which is used in towing vehicles as communication network. As CAN is a very robust bus standard that allows communication distances of up to 40 m with a data rate of 125 kBaud, the ISO-CAN protocol is established in the market on both common plugs ISO 7638 (ISO 11992-2) and ISO 12098 (ISO 11992-3).
Future applications, especially for automated functions, will require a communication with a higher data rate between devices located on truck or trailers of the vehicle combination. Sensor, actuator or telematics data have to be send with low latency. To transmit e.g. camera information of the rear and side view or the load condition, video streams have to be sent in a raw format which may require a data rate of 1 GBit/s or more. A broadband network technology that is already established in the consumer market is Ethernet, described in IEEE 802.3. To enable the deployment of these existing Ethernet standards in automotive network applications, the non-profit, special interest group OPEN Alliance, formed by several companies of the automotive industry and technology providers, released the BroadR-Reach™ automotive Ethernet standard in 2011.
Within the AEROFLEX project an Automotive Ethernet Router Repeater (AE-RR) was developed. It is based on an already existing serial CAN Router Repeater with an additional ISO plug, that is used in trailers to connect

further trailer units, such as a dolly. One AE-RR is mounted on each vehicle unit (truck or trailer) with interfaces for the ISO CAN as well as for common Ethernet devices using a RJ 45 plug. An internal Automotive Ethernet chip routes Ethernet messages within the network including the mandatory ISO CAN messages for communication between e.g. the truck and trailer EBS, which, for this purpose, are wrapped into Ethernet frames. Thus, beside the integration of the AE-RR no additional components or changes in hardware or software of the existing installation is necessary. To provide a generic solution and support vehicles without Automotive Ethernet capabilities, the AE-RR contains a CAN/AE multiplexer to switch between both technologies. Therefore, a conventional vehicle can still communicate via ISO CAN. The availability of Automotive Ethernet capability and the switching sequence is indicated by an additional proprietary message on the ISO CAN. To enable advanced truck trailer communication the AEROFLEX project introduced a new protocol based on the ISO 11992 standard.
Application of the developed technology is only limited by the deviation from the standard in terms of the physical layer, that according to the ISO is restricted to CAN using a two wire bus. This is violated by the integration of the AE-RR in the communication network.

4. Demonstrator vehicle

The concepts described in the former sections were realized in an EMS 1 vehicle combination (see Fig. 7). A MAN 580hp long haul truck provides enough torque and power for operating a 60ton vehicle. Of course, depending on the cycle, the electric drives would allow to use a smaller engine. However, reference tests without electric drives demanded for the larger engine. The truck is equipped with a swap body, underlining the multi-modal approach of AEROFLEX. An appropriate human-machine-interface informs the driver about the current state of the powertrain.

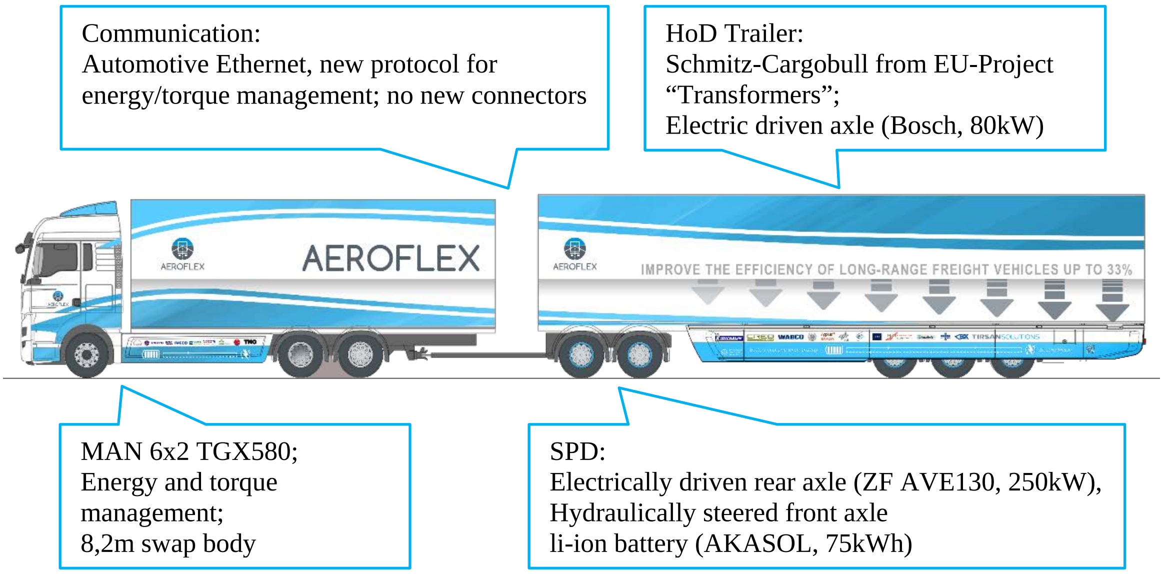

Fig. 7: Demonstrator vehicle realized in the AEROFLEX project including the AEMPT innovations

The selection of the hybrid powertrain components for the SPD was mainly driven by the products available on the market. While the driven rear axle AVE130 from ZF Friedrichshafen fits the power recommendation resulting from the simulation study, the capacity of the lithium ion battery exceeds the value given in section 3 by far. This is due to the combination of energy and power density of the NMC based lithium ion cells widely used in batteries developed for electric vehicles. Due to the relatively low permissible current rates on cell level, a battery configuration with a high number of cells and thus, a high capacity had to be chosen to serve the power demand of the electrically driven axle. Nevertheless, a higher battery capacity in combination with the, currently not realized opportunity of plug-in charging can be an advantage for the use case of autonomous yard operation.
The usage of a low floor driven axle, originally developed for busses, allows for an optimal integration of the battery in the rear part of the SPD (see Fig. 8 and Fig. 9). Thus, the other components of the high voltage system and the cooling system can be installed in the front part. In comparison to a conventional dolly, the electric powertrain results in an additional weight of about 1750 kg.

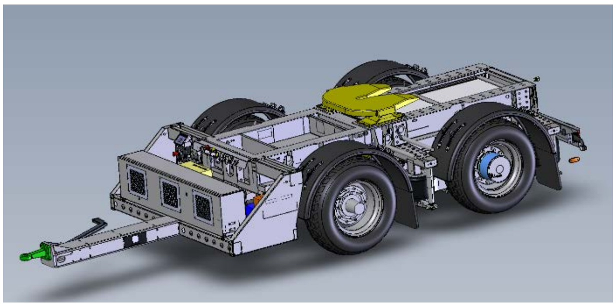

Fig. 8: CAD model of the SPD

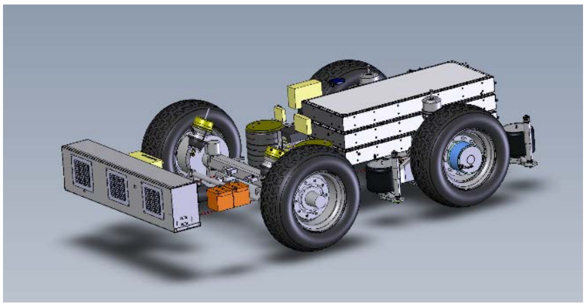

Fig. 9: CAD model of the SPD reduced to the electric powertrain components (driven axle, battery, inverters), steered axle, cooling system and ECUs

5. Summary and Outlook

The paper outlines different aspects of the development and implementation of a distributed powertrain for a long-range freight vehicle, with focus on the electrically driven dolly.

The results from the initial studies show that distributed powertrains can contribute significantly to fuel saving by effectively hybridizing the whole vehicle combination. Although the optimal configuration of EMG and battery vary over the different drive cycles, vehicle combinations and loading conditions, fuel saving between 5% and 17% promise a high potential to reach the project’s overall target of improving transport efficiency by up to 33%.

The feasibility to realize the recommendations regarding powertrain parameters resulting from the above mentioned studies even under very restricted installation space is shown by the development and construction of the SPD. High effort was also put into the vehicle-to-vehicle communication technology due to enable the management of the electric powertrains installed in the towed vehicles as well as to guarantee overall driving stability of such vehicle combinations.

During the next phase of the AEROFLEX project the demonstrator vehicle will undergo an extensive test plan including driving tests on a test track as well as public road testing. The tests comprise different vehicle combinations using conventional trucks and dollies/trailers as well as the advanced vehicles developed in the project. Thus, real world measurements will be generated to evaluate the fuel consumption results of the initial studies. Furthermore, the impact of each innovation in the individual vehicle units can be assessed.

Acknowledgments

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